Design of Hybrid Industrial Solar Drying Unit

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Abstract—This study done for designing industrial solar air heater drying unit with two parts of experimental steps (selecting solar air heater type and other part for controlling outlet temperature through mixing hot and ambient air through static mixture). The experiment done for 6 six days for each type using fabricated glass covered corrugated solar air heater with tow possibility of modifications one of them with fixed absorber plate defined as type one and other one tested with removed absorber plate which defined as type two experiments done with full accessory (air supply fans, temperature mea with same test study using device, fresh air motor controlling RPM and fabricated static mixture. The drying temperature range (45°C to 55°C). Before testing pilot unit calculation of predicted hot air temperature was done for validity of unit then the experiments has been made with pilot unit of solar air heater with fresh air stream and static condition, the result show that solar air heater type one is better for stable results for out let temperature and suitable for working, also the experiments show that, the presented value of temperature of hot mixed air of SAH type one have fitness with set point of controller 90% for day one and day two but for SAH type two the present value haven’t fitness with set point, the reading either high or low than the set temperature, for the other part of study prove that mixing hot air from solar air heater and fresh ambient air is success and control system working properly for the propellant drying process.

Index Terms—Hybrid System; Static Mixture; Solar.

I. INTRODUCTION

Solar energy is the oldest energy source ever used. The sun was adored by many ancient civilizations as a powerful god. The first known practical application was in drying for preserving food [1]. Probably the oldest large-scale application known to us is the burning of the Roman fleet in the bay of Syracuse by Archimedes, Solar is one of great resources which supply our planet with light and energy [1], used in daily activity as clean source of energy ,now the world invest in this sector as sources of energy for industrial application to make both cost and emission low, one of these application is flat plate collector for solar energy (FPC) which has received much attention in the recent years to its properties as simple and lowest operating cost system which offers important environmental benefits which using unexhausted energy and eliminate CO₂ generation form traditional fuel use.

A. Flat plate collector working principle

The flat plate collector for solar energy (FPC) is a special kind of heat exchanger (Fig. 1), [2], that transforms solar radiation energy to internal energy by absorbing solar radiation with absorber plate covered with transparent glass, then the collected heat transferred through a working fluid (air) and it is general description for a way of how the solar energy can be collect and it have many types and it take its name according to its function in this research the author depend on the flat plate collector to rise the temperature of the ambient air to hot air so here the author deal with flat plate collector con be cold solar air heater which known as SAH.

B. Statement of the problem

1) Overview

This study conducted in field of producing smokeless powder that consuming large energy which can be classify as one of highest production cost because of energy and also pollution share participator regarding to emission generated during production steps which can be minimized by depending on solar thermal energy, the process under study is drying process which must done with temperature start from (45°C to 50°C) and must not exceeding 55°C to avoid product chemical disintegration which lead to explosion.

2) Process description

One of very important steps of manufacturing single base propellant drying process which take from (22 up to 25) hr. inside static dryer (trough type dryer) through forced convection ,hot air supply from bottom of tough and pass through propellant grains taking moisture up to specific limit(1-1.8%) ,the hot air supply with temperature 55 °C ,using steam with (194° to200°)C for heating the air from ambient temperature to 55°C max, through air handling unit connected to drying trough with distribution galvanized...
duct, the dryer is loaded with material for drying. Fig. 2 shows schematic diagram explain the old process.

![Fig. 2. Original process diagram](image)

**C. Solar system**

According to day hours of the solar and Sudan county climate, it’s easy to obtain this temperature from sun rise up to sun set so from here the Idea of using of solar air heater growth and will be applicable and can gain [3] (Fig. 4) cost and environmental benefits for day shift for 8 hours of drying, the steam system can be activated at night shift during of absent of solar, but the challenge is how to control the temperature and flow of hot air to satisfy the process requirement so to achieve this the author use scientific way to make this possible .through a pilot unit designated with accessories include solar energy collection(SAH), blowers, connection pipes, measuring and control elements (Fig. 3).

![Fig. 3. Hybrid system](image)

**II. LITERATURE REVIEW**

An experimental application of air heating to drying of soybeans at the Gold Kist plant at Decatur, Alabama, was one of a series of demonstrations of solar industrial process heating sponsored in part by the U.S. Department of Energy. The system, described by Guinn (1978), consisted of 1200 m² (672 modules) of air heating collectors supplying warmed air to the dryer. The air was mixed with additional ambient air, heated by oil to the desired temperature, and used in the drying operation [4]. Since the maximum output from the collectors was less than the energy needs of the dryer, all collected energy could be used (during the drying season) and no storage was provided, in this system, the filter and blower were on the upstream side of the collectors, to put the collectors under positive pressure and avoid ingestion of dusty air into the system where it might become an explosive mixture. The size of the collector array was essentially fixed by the dimensions of a parking lot over which the array was mounted. The collector slope was 15°, chosen as a compromise between performance and greater structural costs associated with larger slopes. The atmosphere in the plant area was dusty, and keeping the collectors reasonably clean was a significant operational problem. Systems of this type, which are designed for small contributions by solar in relation to the total loads, can be operated without energy storage. No energy will be dumped as long as the maximum output of the collector is less than the energy needs of the application at the time the collector maximum occurs. It may be that the time of collector operation would be determined by the process itself (e.g., times when paint spraying is going on or when materials are in the dryer ready to be dried), and under these circumstances storage may be needed (Fig. 5).

![Fig. 4. Global of horizontal irradiation (Sudan)](image)

The Solar Cabinet Dryer at ICT-Mumbai (Visavale, 2009) solar cabinet dryer consisted of an indirect forced convection solar dryer with a solar air collector, a blower for air circulation and a drying cabinet the solar air collector had dimensions of 4 × 5 m. A plain copper sheet painted black was used as an absorber plate for incident solar radiation. It was oriented southward under the collector angle of 31°. The collector and blower system was well insulated to prevent heat losses. The drying cabinet dimensions were length 1.20 m, breadth 0.76 m and height 0.40 m constructed with insulated walls and had 16 shelves. A centrifugal blower (capacity 1000 m³h⁻¹) connected to the
drying cabinet provides a maximum air velocity of 1.0 ms\(^{-1}\). The circulation fan that supplies fresh air has a power of 1.5 kW. During experiments the air velocity, temperature and relative humidity in the cabinet were in the range (0.9-1.0) m/s, (40°-60°) C and 50-65%, respectively [5] (Fig. 6).

![Fig. 6. Pictorial view of Solar Cabinet Dryer at ICT-Mumbai (Visavale, 2009)](image)

A. Author study
Many studies talks about using solar thermal energy for heating air with different designs and uses, also solar air heater units for industrial use are studies but as the author needs so no such design typically applicable to be used in the process mentioned, so this let the author think to design a solar unit meet the requirements of fixed drying temperature and fixed air flow that never available in the previous studies which need controlling of hot air flow, the design take into account the original air handling unit in the factory for supply enough air to the process and hot air from solar will be mixed with the outlet duct of the air handling unit pass to the process through air static mixture to mix two air streams to uniform the final set temperature, the temperature controller will control the flow of ambient air through motor speed control device (VFD) for air handling unit depending on final mixed air temperature at 55°C, this study investigate better design of solar air heater, this system must be check before investments through pilot unit with full preparations.

B. Design advantages
1- No need to establish a huge unit to deliver required air only amount of air required for rising the temperature of original air system.
2- Minimize the number of solar collector units which minimize required area of collector.
3- Keep the original system ready for operating with old heating system.
4- Low construction and maintenance cost.
5- No additional control devises only some small modification enough.

C. Scope of work
The project has to focus on the following scopes in order to achieve the objectives:
1- Conducting literature review regarding flat plate collector (FPC) and concept of mixing tow stream of hot and cold air.
2- Investigating performance of (SAH) with tow type (SAH with absorbing plate and without absorbing plate).
3- Analyze the data obtained from the experiments.
4- Investigating design study stage for the requirement (Characterize solar process heat integration point) of industrial scale unit regarding to the area, location referring to drying building, piping and integration point.
5- Contacting local climate station for confirmation of radiation information.

III. MATERIALS AND METHODS

The testing stage include of flexible design of SAH for testing and comparing the performance of (SAH with absorbing plate and SAH without absorbing plate), the design of pilot unit is taken into account adiabatic design with good thermal insulation and better solar heat collection through dimension and glass thickness. For testing the SAH will face south with inclination angle 16 degrees similar to latitude angle [6]. Below the fabrication steps:

A. Main body of SAH
The testing model consist of six component made from local material an designed firstly in the software before fabrication to avoid wasting time and material, about the dimensions was selected by take in account the collection area which make calculation for industrial scale simple, so the outside dimensions is 108 cm width and 157 cm length include absorbing area and distribution chamber and the effective area is 150 length and 100 cm width and height 13 cm, ,SAH cover with 4mm window glass [7] with space [8] 3m over absorber plate (Fig. 7).

![Fig. 7. Solar Air Heater](image)

B. Description of component
The outside body was made from wood to assist insulation and to protect heat exchange between SAH and surrounding with thick 2cm, the next is insulation material from polystyrene which available for domestic use, this insulation material fixed inside the wooden box for 5 face, for sides and bottom as below in (Fig. 8).
C. Hot air flow path

The air bath made from normal steel with corrugated shape to provide maximum surface area supported with fins (Fig. 9 and Fig. 10 respectively). To provide better heat exchanging between air and heated surface, tow chamber for controlling air path are distributed as in Fig. 9 below:

D. Absorbing plate

This plate was made of normal steel with thickness 0.3 mm with dimension 1m width and 1.2 m length, fixed over corrugated surface of SAH body to investigate the better performance after testing two cases SAH without absorbing plate (Fig. 10) and the other case testing SAH with absorbing plate to select the better for final design Fig. 11 and Fig. 12 show these two cases.

For testing all accessory connected such as controlling device and blowers for hot and ambient air (Fig. 13), both hot and ambient air streams mixed together with static mixture (Fig. 14).

Note: This mixer was designed by the author
E. Steps of testing of pilot unit

All individual component checks for validity and the test steps as follow:
1. Preparing measuring and controlling device of velocity and hertz.
2. Testing and recording of solar air heater without air supply to confirm the ability of local material and to calculate expected exit temperature of outlet air stream.
3. Testing and recording of solar air heater with air flow without mixing with fresh air.
4. Testing pilot unit with fixed hot air flow rate and variable cold air stream flow rate and set point of mixed air stream temperature, then recording of other system parameter with set temperature 55°C (with recording of present temperature valve for mixed air at set point, ambient air flow through hertz and corresponding air flow, hot air temperature and ambient air temperature).
5. Removing absorbing plate from the corrugated absorbing surface and repeat step 4 to compare the performance without absorbing plat to select the better deign for industrial unit.

F. Mathematical modeling

1) Part 1: heat gain by SAH:

The gain heat absorbs from the solar by the SAH calculation is required to determine losses which can be rise from nature of both material and quality of material used and fabrication of SAH, then the heat gain can be calculated from (1) to (8) [9].

\[ Q_a = A c T_a[I (τa) - U_l(T_{pm} - T_a)] \]  
\[ F_R = F' . F'' \]  
\[ F' = 1 + \frac{UL}{h_l}\left[\frac{1}{h_L} - \frac{1}{h_f}\right]^{-1} \]  
\[ h_l = \frac{4\alpha T^{-3}}{\frac{1}{h_L} + \frac{1}{h_f}} \]

Total losses coefficient\( U_1 \):
\[ U_1 = U_t + U_b + U_e \]  

First Top losses equation:
\[ U_t = \left( \frac{N}{T_{pm}} \right) + \frac{1}{h_w} \]  
\[ + \frac{\sigma(T_{pm} - T_a)(T_{pm}^2 - T_a^2)}{k_p + 0.000591 h_w} \]

Bottom losses:
\[ U_b = \frac{(U_A)_{edge}}{A_e} \]  

Edge losses:
\[ U_e = \frac{(U_A)_{edge}}{A_e} \]  

2) Part two:

Using (5), (3), and (2) to calculate expected exit hot air temperature as preparing step of testing:
\[ T_{e} = T_{e} - \frac{1}{h_w} \]  

For calculating \( h \), Nusselt number must be calculated. Because the air flow in side closed duct one side heated and the flow of air turbulent flow so [10]:
\[ h = \frac{Nu k}{DN} \]
\[ Nu_l = 0.0158 \]  

Equation (11) valid for \( 2300 < Re < 5 \times 10^6 \)

Then \( Re \) number [8] must be calculated from equation below:
\[ Re = -\frac{U D h}{\mu} \]

The value of air properties \( (\rho, k, \mu, cp) \) can be obtained from tabulated data at \( T_{film} \) which can be calculated from (13).
\[ T_{film} = 0.5(T_{amb} + T_{Prc}) \]

Then \( D_h \) can be calculated from (14):
\[ D_h = 4^\alpha A/l \]

A and P can be calculated from Fig. 15 below:

Fig. 15. Dimension of trapezoid duct of SAH

So:
\[ A = \frac{(a+b)h}{2} \]

And:
\[ P = a+b+c+d \]

3) Part three:

Calculating mass flow rate in kg/s using (17) and which include measured diameter of outlets of air streams entering the static mixer and also depend on density of air at specific temperature from air properties table.
\[ \dot{m} = A_p v \]  

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According to the Law of Conservation of Energy, (18) calculates the air stream mixing from derivation of equation of math and heat balance as in Fig. 15.

\[
m_{\text{cold}} = \frac{m_{\text{cold}}(T_{\text{hot}} - T_{\text{set}})}{(T_{\text{set}} - T_{\text{cold}})}
\]

(18)

The test will be conducted for three days two times for SAH with absorbing plate and SAH without absorbing plate and then the reading recorded then the calculation done for cold air flow rate to determine the solar collecting area required to meet industrial requirement.

4) Part four:

Scaling up to industrial scale unit depending on calculation the hot air required can be calculated from experiments and energy required can be calculated from (19) by dividing energy required and heat gain from pilot unit the number of SAH can be calculated, system component, layout of industrial unit depend on the calculation of number of rows and distances between them to avoid shadow as in Fig. 17.

\[
Q_u = m_{\text{cp}}(T_{pm} - T_a)
\]

(19)

\[
D = \frac{\sin(180 - (\theta + \beta))}{\sin \beta}
\]

(20)

The shadow must be avoided between collectors’ rows and also collectors’ groups using (19).

IV. RESULTS AND DISCUSSIONS

The data collected from experiments with value of fixed hot air flow and variable cold air temperature controlled through VFC and velocity took from recoded hertz with corresponding velocity (Fig. 18), the experiments done form 9:00 AM to 4:00 PM which shows the solar system is useful as a support system and the effect of absorbing plate is significant which achieve stable result of final set (Fig. 5), temperature more than the collector without absorbing plate, also calculated and measured outlet temperature of hot air have no significant difference Fig. 19. The calculated from date obtained from experiments and equations in part III then value of heat gain for average reading for SAH with absorbing plate is 666.77 watt with overall heat loss 5.52 W/m² C◦ and aperture area 1.5 m² and heat removal factor 0.7, so for solar system the maximum air flow is 4 kg/s which need 140 unit to be useful if we use this design and material of SAH under study, Fig. 13 shows the design of layout of solar system and existing drying system connected together SAH connected in parallel to avoid heat rising in series and supply with filter at upstream and suction fan at downstream [11]. Fig. 14 shows layout of SAH under study.

Fig. 20 shows SAH also for three days tested with absorbing plate three days, Fig. 20 shows results for SAH without absorbing plate for individual tests results on September and October Fig. 22, 23, 24 and Fig. 25, 26 respectively.
This paper discusses the type of SAH selected for design industrial scale from the results obtained, both material and fabrication duality led to significant effect, the absorber plate maintain the distribution of temperature through SAH, which became clear in second test after removing absorber plate the present value of outlet mixed air temperature either too high than the set point or lower, the mixing of two air streams through static mixture show the validity of depending of mixing system for solar heat for obtaining set point temperature for whole system. The predicted hot air temperature from calculations show some differences which indicated heat and air leaks for SAH. This system effective and dependable, in case of using better insulation, and material such as crystal glass with high transmittance and absorbing plate with high heat transfer coefficient coated with selective coating will reduce the number of industrial units by increasing heat gain by SAH unit.

V. CONCLUSIONS AND RECOMMENDATIONS

Fig. 20. Required air flow every hour on 20 Sep

Fig. 21. Comparing between air mass flow on 23 Sep

Fig. 22. Comparing between air mass flow on 24 Sep

Fig. 23. Cold air required on 10 Oct

Fig. 24. Cold air required on 11 Oct

Fig. 25. Cold air required on 12 Oct

Fig. 26. Layout of SAH array connected to process units

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LIST OF ABBREVIATIONS

FPC: flat plate collector
Hz: hertz
RPM: Revelation per mint
SAH: Solar air heater
VFC: variable frequency converter

NOMENCLATURE

A: cross sectional area m²
Ac: aperture area of collector m²
Cp: heat capacity
D: distance between collector arrays
e: solar angle
h: heat transfer coefficient
h w: convective heat transfer coefficient (Kj.h⁻¹.m⁻².k⁻¹)
v: Air velocity (m/s).
e= 0.430(1− 100/T)
F': efficiency factor of the solar air heater
F'' : collector flow factor
f(1 + 0.089hw− 0.1166hwεp)(1 + 0.07866N)
FR: heat removal factor
hv: radiant heat transfer coefficient
h: heat transfer coefficient
Heat quantity
I: solar intensity
k: insulation thermal conductivity
K: thermal conductivity
L: edge thickness
N: number of glass cover
Nu: Nusselt number
Q u: heat quantity gain by the air (watt)
Re: Reynolds number
Ta: ambient temperature
Te: exit temperature °C
Tf: Temperature Film
Tm: mean plate temperature
Ub: bottom losses coefficient (Kj.h⁻¹.m⁻².k⁻¹)
Ue: edge losses coefficient (Kj.h⁻¹.m⁻².k⁻¹)
Ut: top losses coefficient (Kj.h⁻¹.m⁻².k⁻¹)
UA: edge loss coefficient
UL: overall heat losses coefficient (Kj.h⁻¹.m⁻².k⁻¹)
NOMENCLATURE

V: velocity ms⁻¹
W: Watt
GREEK LATER

Θ: solar angle
ε1: emissivity of the glass cover,
ε2: absorbing plate
ε g: emittance of glass (0.84)
ε1: emittance plate
β: collector tilt (deg)
μ: Air viscosity (Ns/m²) at Tf
ρ: Density of air (kg/m³) at Tf

REFERENCES


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